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DEVELOPMENT OF HERMETIC SWING COMPRESSORS FOR CO_2 REFRIGERANT

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ABSTRACT

Due to global environmental concerns natural refrigerants are drawing more and more attention in the refrigeration and air conditioning industry. Among them, particularly CO_2 is easy to apply to refrigeration system, because it has hardly any problems of toxicity and flammability and, in addition, is obtainable at low cost. Therefore, we have developed a compressor for CO_2 heat pump water heater that can provide high temperature water at low running cost.

From the points of physical properties, the density of CO_2 is high and its refrigeration capacity per unit volume is large. It means that the displacement of CO_2 compressors becomes small and, as a result, the influence of leakage on capacity becomes larger and the volumetric efficiency tends to be lower. In addition, its operating pressure is high and the differential pressure is large. Due to a large differential pressure, leakage increases and to maintain the reliability becomes difficult.

Therefore, we focused a swing compressor that can maintain high efficiency and reliability even under a large differential pressure. For high efficiency, we designed the dimensions of the cylinder and the clearance of rotating parts to minimize the leakage gap. For high reliability, we carried out a stress analysis for the parts which receive a large differential pressure. The durability tests show that the adopted methods resulted in no problems around the sliding parts such as a bearing.

As a result, we achieved a high seasonal COP of more than 3.0 by the CO_2 heat pump water heater mounted with the compressor exclusively designed for CO_2.

INTRODUCTION

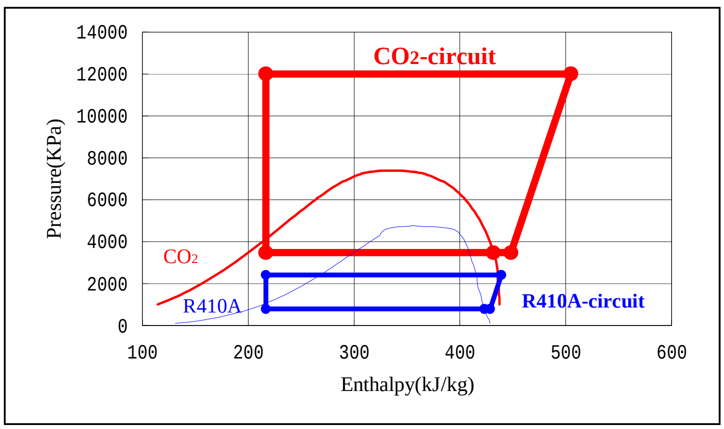
In recent years the concern for natural environment such as ozone layer depletion and global warming is growing. Under these circumstances, natural refrigerants such as CO_2, HC and ammonia are drawing attention as substitutes for HFCs. Among these refrigerants CO_2 in particular has advantages of nontoxicity, nonflammability and low cost. Therefore, research and development [(1), (2), (3)] in CO_2 as a refrigerant for air conditioning and heat pump systems is growing.

Under these circumstances the residential CO_2 heat pump water heater have been launched into the market since February 2002 by Daikin industries Ltd. This unit gives energy saving of more than 70% in comparison with the conventional electric water heater and, in addition, by utilization of midnight electricity rate the running cost is cut down by 20 to 25% based on the electricity rate system in Japan.

We developed a swing compressor with high efficiency and reliability for CO_2 heat pump water heaters. This paper explains the construction and characteristics of a swing compressor mounted on the CO_2 heat pump water heater.

COMPRESSOR TYPE

Fig. 1 shows typical operating conditions with CO_2 and R410A. As mentioned before, it is necessary to solve the technical problems such as a compressor for CO_2 is leakable and its operating pressure difference is high. The following study explains how these problems are solved.



Though reciprocating compressors are less leakable because the sealing area is limited only around the pistons, their cost tends to be higher due to the number of parts and, in addition, their vibration is larger. Though scroll compressors trend to have less vibration, it is not suitable to maintain the efficiency because they have many points of leak due to multi chamber compression construction. In addition, it is difficult to maintain the reliability, because the thrust load gets larger due to high operating pressure of more than 10MPa. Since the rotary type has a construction of less leakage, higher efficiency can be expected. However, the reliability is a problem, because it is extremely difficult to maintain lubrication of vane under large differential pressure. If two stage compression type is adopted to avoid this problem, their structure becomes complicated because the number of parts is more than that of single stage type.

Figure 1. P-H Chart of CO_2 and R410A

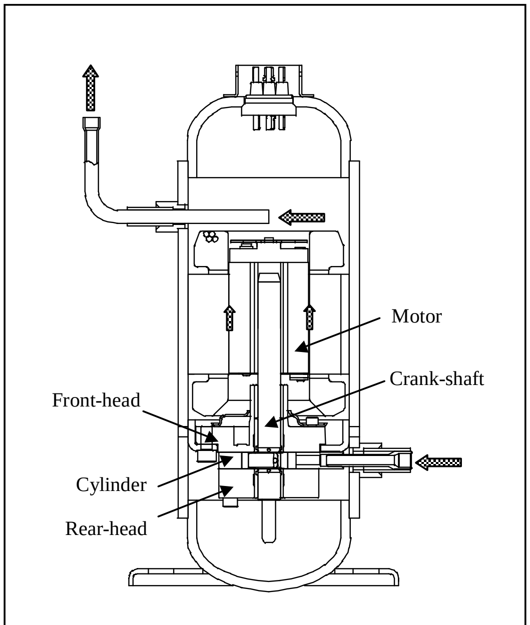
In comparison with these compressors, the swing type has more advantages such as less leakage and no poorly lubricated parts like vanes of the rotary type. Furthermore, these advantages enable us to adopt the single stage compression mechanism. The number of parts can be reduced by adoption of this mechanism. Though adoption of a high pressure shell brings a disadvantage of a thick shell, it brings an advantage of less oil circulation rate and the reliability is maintained. This is because the oil inside the compressor shell is separated from the refrigerant. From these points of view, we adopted the swing compressors that have many advantages for the CO_2 refrigerant.

CHARACTERISTICS OF CO_2 SWING COMPRESSOR

Basic Construction

Fig.2 shows the section of a compressor for CO_2 and Fig.3 shows the scheme of its compression mechanism and Table1 shows its summary specifications. Its basic construction and the flow of refrigerant and oil are identical to that for R410A and are as simple as that for R410A.

In addition, we adopted the Interior Permanent Magnet (IPM) synchronous motor [4] that are able to operate with high efficiency from low to high speed. This is because IPM motors generate not only magnet torque but also the reluctance torque by using the rare-earth permanent magnets with high magnetic energy density.



Compression type	Single stage swing compressor
Motor type	Interior Permanent Magnet synchronous motor (variable speed)
Displacement	3.7cc

Table 1. Summary specification of CO_2 swing compressor

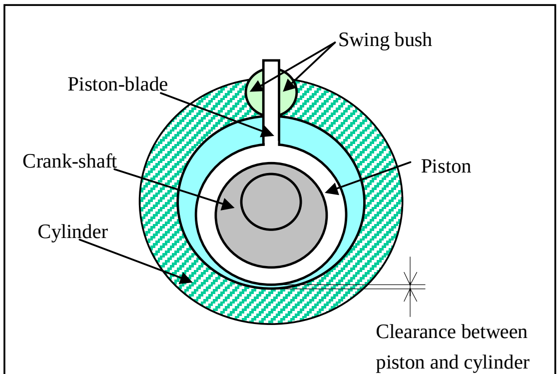


Figure 2. Cross-section of CO_2 swing compressor

Figure 3. Scheme of compression mechanism of CO_2 swing compressor

Characteristics

As for the issues that the compressor is leakable from compression chamber to suction chamber and the pressure difference is large, we gave consideration in design to reduce the leak passage area and the leak clearance, and carried out stress analysis to the parts that receive a large differential pressure as mentioned below.

1. Minimization of leakage loss

In order to minimize the leakage during operation, it is necessary to make both the leak passage area and the leak clearance small. As for the former, it is necessary to design the items of cylinder so that the leak passage can be minimized. As for the latter, it is necessary to assemble the compressor so that the clearance between the cylinder and the piston can be minimized.

It is known from the past researches [5] that volumetric efficiency and indicated efficiency increase as the ratio of H/D decreases, where H means cylinder height and D means cylinder diameter. This is due to decrease of the leakage from clearance between the piston and the cylinder and the heat loss. We designed to minimize H/D within the limit of the bearing reliability. We also adopted a high viscosity oil to minimize the cylinder height within the allowable mechanical loss.

2. Stress analysis for parts which receive a large differential pressure

We conducted stress analysis by FEM of piston blades and front head, which receive a large differential pressure.

As for the piston blade we conducted the stress analysis for both CO_2 and R410A type at the lower dead point where the applied load is maximized, because a piston blade receives a differential pressure between the compression and suction room. Fig.4 and Table 2 show the calculated results. The maximum stress occurs at the base of piston blade. The test results show that the maximum stress of the CO_2 compressor is no more than that of the R410A compressor. We assumed that this is because the eccentricity of the CO_2 type is small.

As for the front head, we conducted the stress analysis based on the assumption that the maximum suction pressure area occurs at the upper dead point, because a front head receives a differential pressure between the suction room and the shell. Fig.5 and Table 3 show the calculated results. The maximum deflection occurs around the discharge valve where the thickness is small. The test results show that deflection of the CO_2 compressor is no more than the R410A compressor. We assumed that this is because the eccentricity of the CO_2 compressor is small and the area receiving the differential pressure is also small and the thickness external part is larger than that around the discharge valve.

Refrigerant	R410A	CO_2
Pressure difference	3.9MPa	8.5MPa
Ratio of stress	100%	94%

Table2. Stress analysis results of Piston-blade

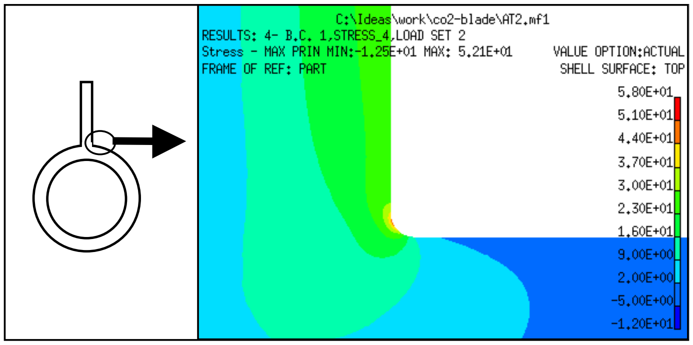


Fig4. FEM analysis of Piston-blade

Refrigerant	R410A	CO_2
Pressure difference	3.9MPa	8.5MPa
Ratio of deformation	100%	54%

Table3. Deformation analysis results of front-head

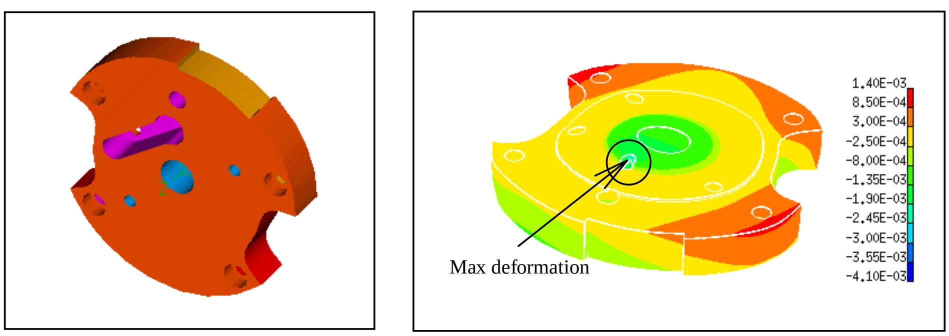


Fig5. FEM analysis of front-head

EXPERIMENTAL PERFORMANCE RESULTS OF CO_2 SWING COMPRESSOR

For evaluation of CO_2 swing compressor efficiency under various conditions, we made a performance evaluation device shown in Fig.6. The refrigerant circuit is made up of a water heat exchanger to function as a gas cooler and a refrigerant heater to function as an evaporator. The refrigeration capacity is measured with a refrigerant mass flow meter. For setting conditions, the high pressure is controlled by water flow rate to the gas cooler, the refrigerant circulating rate is controlled by the electric expansion valve and the compressor suction temperature is controlled by heater input.

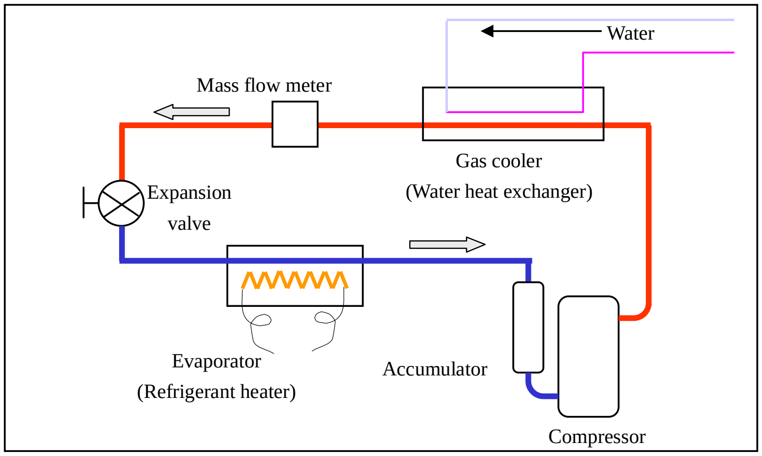


Figure 6. Performance evaluation device of CO_2 compressor

Fig. 7 and Fig. 8 show the test results of influence of compressor frequency on volumetric efficiency and total compressor efficiency respectively. The test results show that total compressor efficiency keeps high level between 60 and 90 rpm, the range of a compressor usually used.

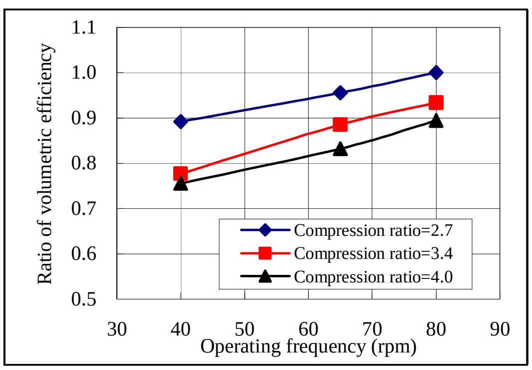


Figure 7. Influence of operating frequency on volumetric efficiency

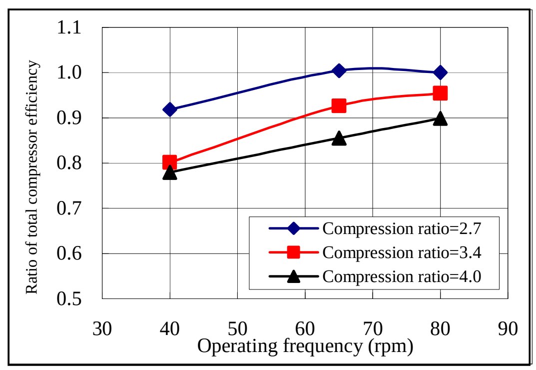


Figure 8. Influence of operating frequency on total compressor efficiency

Fig. 9 and Fig. 10 show the test results of influence of pressure ratio on volumetric efficiency and total compressor efficiency respectively. The test results show that efficiency decreases as an increase of pressure ratio. The smaller the compressor frequency becomes, the greater the trend of efficiency drop becomes.

Fig. 11 and Fig. 12 show the test results of influence of clearance between piston and cylinder on volumetric efficiency and total compressor efficiency respectively. Here, we set the clearance of R410A compressor as 1.0. It shows that to set the clearance 1/2 to that of R410A compressor results in increase of efficiency by almost 10%. Therefore we set the clearance between parts of a compressor for CO_2 smaller to approximately 1/2 than that for R410A and secured the efficiency.

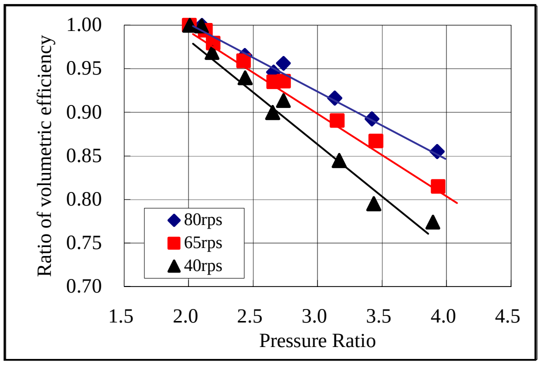


Figure 9. Influence of pressure ratio on volumetric efficiency

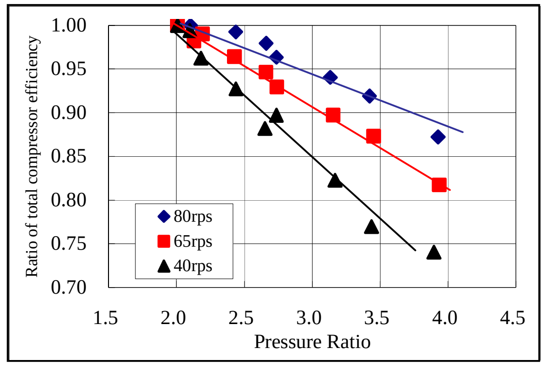


Figure 10. Influence of pressure ratio on total compressor efficiency

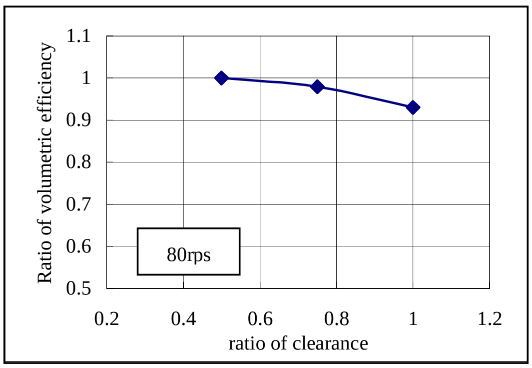


Figure 11. Influence of clearance on volumetric efficiency

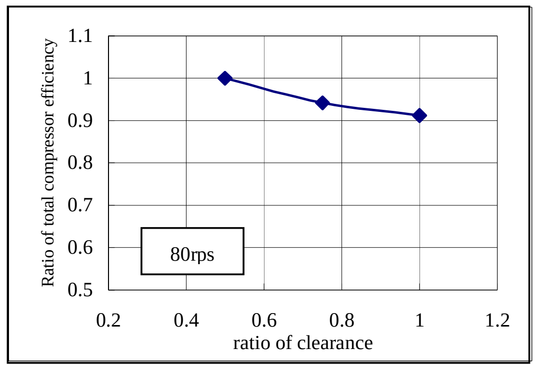


Figure 12. Influence of clearance on total compressor efficiency

Fig. 13 shows the pressure measurement of the cylinder internal plenum of a swing compressor for CO_2. In spite of the circumstance of a large differential pressure, it shows that a high indicated efficiency is successfully realized with the swing compressor for CO_2 by minimization of leakage pass.

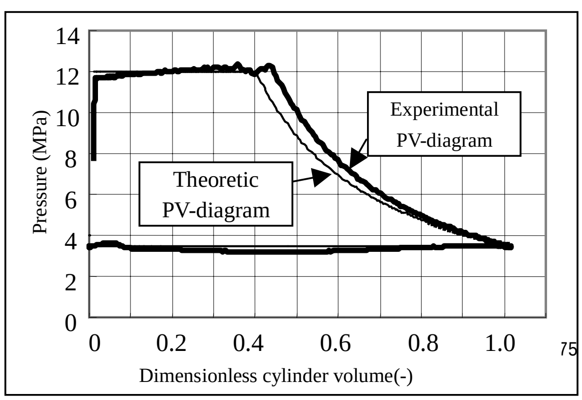


Figure 13. Experimental pressure-volume diagram

DURABILITY TEST

We conducted reliability evaluation tests of a CO_2 heat pump water heater under the conditions shown in Table 4. We evaluated the sliding parts and oil under accelerated conditions. Even after the tests of 2000 hours, no problems occurred such as abrasion of sliding part, total acid number rise of oil. We concluded that the oil film of the bearing was maintained and no deterioration of oil occurred under the sever conditions.

Discharge/ Suction pressure	12/3.5MPa
Discharge temperature	110-130°C
Test period	1000-2000hours

Table4. Condition of durability test

CONCLUSIONS

We achieved high efficiency and reliability of CO_2 compressors by optimizing the design of swing compressors for minimization of leakage and reviewing the thickness of parts that receive a large pressure difference. These compressors are mounted on the CO_2 heat pump water heaters that are already commercialized and contribute to energy saving through a high energy efficiency of COP 3 or higher.

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